The emission reduction potential of electric transport modes in Finland

Jenu, Samppa; Baumeister, Stefan; Pippuri-Mäkeläinen, Jenni; Manninen, Aino; Paakkinen, Marko

Published in:
Environmental Research Letters

DOI:
10.1088/1748-9326/ac2440

Published: 01/10/2021

Document Version
Publisher's final version

ENVIRONMENTAL RESEARCH
LETTERS

LETTER • OPEN ACCESS

The emission reduction potential of electric transport modes in Finland

IOP Publishing Environ. Res. Lett. 16 (2021) 104010 https://doi.org/10.1088/1748-9326/ac2440

ENVIRONMENTAL RESEARCH
LETTERS

OPEN ACCESS

RECEIVED
18 June 2021

REVISED
31 August 2021

ACCEPTED FOR PUBLICATION
7 September 2021

PUBLISHED
21 September 2021

LETTER

The emission reduction potential of electric transport modes in Finland

Samppa Jenu[1,*], Stefan Baumeister[2,3], Jenni Pippuri-Mäkeläinen[1], Aino Manninen[1] and Marko Paakkinen[1]

[1] VTT Technical Research Centre of Finland Ltd., PO Box 1000, FI-02044, Espoo, Finland
[2] University of Jyväskylä, School of Business and Economics, PO Box 35, FI-40014 Jyväskylä, Finland
[3] University of Jyväskylä, School of Resource Wisdom, PO Box 35, FI-40014 Jyväskylä, Finland
[*] Author to whom any correspondence should be addressed.

E-mail: samppa.jenu@vtt.fi

Keywords: modal shift, electric transport modes, electric aviation, greenhouse gas emissions, travel time

Supplementary material for this article is available online

Abstract

The transportation sector has become the fastest growing source of greenhouse gas (GHG) emissions. One solution to mitigate the impacts is a shift towards electric modes. Where previous studies have only focused on the replacement of individual modes, our study presents a more holistic approach by comparing land-based, water-based and airborne transportation modes. We study the GHG emission reduction potentials of electric cars, buses, trains, ferries and aircraft in comparison to existing modes on 34 routes within Finland and across the Baltic Sea to Sweden and Estonia. By comparing the GHG emissions in carbon dioxide equivalents (CO_2-eq) per passenger kilometer for each mode, we also consider the emissions generated from battery production as well as the differences in the energy mix from electricity production of the three studied countries. In addition to CO_2-eq emissions per passenger kilometer, we also take real door-to-door travel times into account. Our study found that electric transportation modes possess great potential for emissions reduction. Nevertheless, depending on the energy mix used for electricity production, the emissions of electric transportation modes can exceed those of existing modes significantly. In addition, the emissions generated by battery production can have a significant share of the total emissions and should therefore always be considered. Finally, while also taking into account the door-to-door travel times, our study identified the great potential of electric aircraft to provide a less carbon intensive transportation option paired with short travel times starting on routes beyond 300 km where no high-speed rail exists as well as on routes across the water.

1. Introduction

The latest IPCC special report calls for drastic reductions of greenhouse gas (GHG) emissions to limit global warming to 1.5 °C above pre-industrial levels (Rogelj *et al* 2018). The transportation sector is the 2nd largest producer of carbon dioxide, responsible for 24% of global emissions (IEA 2017), but it has become the fastest growing cause of GHG emissions (Sivak and Schoettle 2016). Between 1990 and 2015, the sector's emissions grew by 68% (IEA 2017).

One solution to mitigate the climate impacts of the transportation sector is modal shift (Borken-Kleefeld *et al* 2013, Baumeister 2019). There are numerous studies that have examined the emissions reduction potentials of a modal shift among existing transportation modes (Dalkic *et al* 2017, Kaack *et al* 2018, Baumeister and Leung 2021), but only a few have discussed the potential of a shift towards new modes of electric transportation. These studies have, however, looked at individual modes, such as a modal shift from conventional to electric cars (Jung and Koo 2018, Ortar and Ryghaug 2019), conventional buses to electric buses (Teoh *et al* 2018, Nordelöf *et al* 2019) or conventional aircraft to electric aircraft (Brdnik *et al* 2019, Baumeister *et al* 2020). To date, there are no studies that provide a holistic approach to a modal shift from existing to fully electric transportation modes on a door-to-door basis and which consider not only land-based but also water-based and airborne transportation modes.

Our study focuses on the GHG emission reduction potential of a modal shift from existing to fully electric transportation modes. We compare existing cars, buses, trains, ferries and airplanes with their electric counterparts. We study the emissions reduction potential of electric in comparison to existing transportation modes on 34 routes within Finland and from Finland to Sweden and to Estonia. In addition to CO_2-eq emissions per passenger, we take real door-to-door travel times into account.

In addition to our holistic approach, we consider battery degradation by allocating battery production emissions to the use phase emissions when comparing the CO_2-eq emissions per passenger, which has received little attention in the literature to date (Hoekstra 2019, Kawamoto *et al* 2019). Because our study is cross-national, we are able to consider the carbon intensity of the electricity grid of the three studied countries, which significantly affects the CO_2-eq emissions of electric transportation modes (Yuksel *et al* 2016, Moro and Lonza 2018, Zhang and Fujimori 2020).

2. Methodology

2.1. Routes

Routes from two different cities in Finland were examined: routes from Helsinki and routes from Vaasa. In contrast to Baumeister *et al* (2020) and Baumeister (2019), the aim was to select a wider range of domestic routes in Finland, as well as some routes across the Baltic Sea to neighboring countries, where modal shift between different transportation modes seemed feasible. The routes from the capital Helsinki included 15 domestic routes to major Finnish mainland cities. In addition, four routes across the Baltic Sea were considered: from Helsinki to Tallinn, Tartu, Mariehamn and Stockholm. The routes from Vaasa included ten domestic routes to major Finnish mainland cities, and routes across the Baltic Sea to Mariehamn and four cities in Sweden. The routes were considered to start and end at the main railway station of the city. If there is no railway station in the destination city, the end point of the route was the travel center of the city or similar central location.

2.2. Calculation of CO_2-eq emissions

The emission comparison focused on operating phase emissions, and the GHG emissions were calculated in carbon dioxide equivalents per passenger kilometer (CO_2-eq/pkm). In addition to CO_2 also CH_4 and N_2O emissions were considered in our study. The formula for calculating CO_2-eq emissions can be found in section 1.1 in supplementary information (SI) (available online at stacks.iop.org/ERL/16/104010/mmedia). For conventional vehicles, emissions from fuel combustion were considered, whereas for electric vehicles, emissions from electricity generation and emissions from battery production were considered. The lifespan of electric vehicle batteries is limited due to battery degradation (Han *et al* 2019), and in the most demanding applications, the battery may need to be replaced before the end of the vehicle's life cycle is reached. Therefore, the battery production emissions should be considered when calculating the real operating phase emissions of the vehicle. It was assumed that there is no significant difference in the manufacturing emissions of conventional vehicles and electric vehicles if battery production emissions are excluded. The assumption is supported by the results of recent studies comparing the life cycle emissions of conventional and electric cars (Wu *et al* 2018, Kawamoto *et al* 2019, Temporelli *et al* 2020, Yang *et al* 2021), and conventional and electric buses (Nordelöf *et al* 2019).

2.2.1. Battery production CO_2-eq emissions

Battery production CO_2-eq emissions represent a significant proportion of the life cycle CO_2-eq emissions of an electric vehicle. Three lithium-ion battery chemistries are commonly used in electric vehicles: lithium nickel manganese cobalt oxide (NMC), lithium nickel cobalt aluminum oxide (NCA) and lithium iron phosphate (LFP). The CO_2-eq emission data of battery production used in many older studies do not correspond to the emissions of mass produced batteries (Hoekstra 2019), and therefore only the most recent available data were used in this study. The production emission data of NMC, NCA and LFP batteries presented in table 1 were collected from the latest scientific articles (Hao *et al* 2017, Peters *et al* 2017, Dai *et al* 2019, Kelly *et al* 2019, Mohr *et al* 2020, Sun *et al* 2020), reports (Emilsson and Dahllöf 2019, European Comission 2020) and public electric vehicle manufacturers' reports (Tesla 2019, Polestar 2020).

2.2.2. Electricity production CO_2-eq emissions

The carbon intensities of electricity consumed from the Finnish, Swedish and Estonian grid were obtained from Moro and Lonza (2018): 211 g CO_2-eq kWh^{-1} in Finland, 47 g CO_2-eq kWh^{-1} in Sweden, and 944 g CO_2-eq kWh^{-1} in Estonia. The large difference between the Estonian figures and the Finnish and Swedish ones is due to the high share of fossil fuels in the Estonian electricity production. On the contrary, the share of renewable energy sources and nuclear power is high in Finland but even higher in Sweden. The figures are the carbon intensities of electricity consumed at the low voltage section of the grid, so they take into account the losses in the distribution network (Moro and Lonza 2018). In addition, for battery electric vehicles the charging efficiency was estimated to be 90%. In the calculations, the carbon intensity of consumed electricity was chosen according to the country in which the vehicle is operated. For electric aircraft or ferries operating between two

Table 1. Battery production emissions.

Reference	Battery production (kg CO_2-eq kWh^{-1})		
	NMC	NCA	LFP
European Comission (2020)	74–79	—	—
Sun *et al* (2020)	124.5	—	—
Mohr *et al* (2020)	76	85	100
Polestar (2020)	89.7	—	—
Kelly *et al* (2019)	65–100	—	—
Dai *et al* (2019)	73	66	55
Emilsson and Dahllöf (2019)	64–106	—	—
Tesla (2019)	—	69.3	—
Hao *et al* (2017)	104	—	109
Peters *et al* (2017)	160	116	161
Mean	96.8	84.1	106.3
SD	±27.1	±19.8	±37.7

Table 2. Transport modes and their use phase emissions. Emissions from electricity generation are calculated based on the carbon intensity of electricity consumed in Finland.

Transport mode	Vehicle	Load factor	Battery (g CO_2-eq pkm^{-1})	Electricity (g CO_2-eq pkm^{-1})	Fuel (g CO_2-eq pkm^{-1})	Total (g CO_2-eq pkm^{-1})
Conventional aircraft (<400 km)	ATR72 turboprop	0.73	—	—	124.49	124.49
Conventional aircraft (>400 km)	Airbus A320 jet engine	0.73	—	—	157.77	157.77
Electric aircraft (<400 km)	Heart Aerospace ES-19	0.73	12.56	30.43	—	42.99
Electric aircraft (>400 km)	Eviation Alice	0.73	16.63	40.28	—	56.91
Diesel train	Diesel driven railcar	0.40	—	—	66.85	66.85
Airport train	FLIRT Sm5 train	0.35	—	14.98	—	14.98
Intercity train	InterCity Sr2 train	0.40	—	11.39	—	11.39
High speed train	High speed train	0.40	—	20.47	—	20.47
Diesel coach (regional traffic)	Diesel coach	0.28	—	—	40.00	40.00
Electric bus (commuter traffic)	Yutong E12 electric bus	0.42	6.24	17.18	—	23.41
Electric coach (regional traffic)	BYD C9 electric coach	0.28	6.99	19.37	—	26.36
Conventional car	Avg gasoline/diesel car	0.38	—	—	73.92	73.92
Electric car	Tesla Model 3	0.38	11.06	18.78	—	29.84
Conventional ferry	LNG ferry	0.50	—	—	99.00	99.00
Electric ferry (82 km route)	Electric ferry	0.50	15.35	98.63	—	113.99

countries, an average of the carbon intensities of the two countries was used.

2.3. Transport modes

The transport modes from different routes included conventional aircraft, electric aircraft, train, diesel coach, electric coach, conventional car and electric car (see table 2). If a combination of transport modes had to be used to reach the final destination (e.g. the need to cross the Baltic Sea by ferry), conventional modes were combined with conventional modes and electric modes with electric modes, if available. For short connecting trips (e.g. from the airport to the railway station) an airport train or electric bus was used.

One important parameter in the calculation of CO_2-eq emissions per passenger kilometer for each transport mode was the load factor of the vehicle. The load factor used in this study for conventional and electric aircraft was 0.73 (Finnish Transport Agency 2017). For other transport modes the load factors correspond to average load factors in Finland, and the numbers were retrieved from VTT's LIPASTO database (VTT 2017).

The CO_2-eq emissions per passenger kilometer for different transport modes are presented in table 2

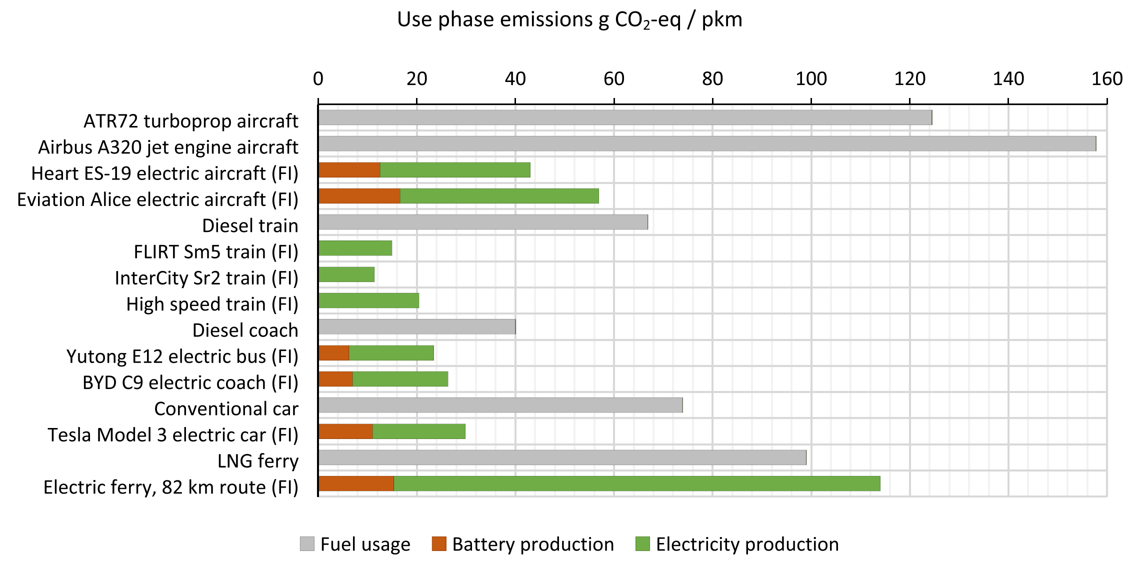

Figure 1. Comparison between use phase emissions of different transport modes using Finnish electricity carbon intensity and typical load factors in Finland.

and figure 1. The reference vehicles used in the calculations for each transport mode are presented in the following subsections. Additional information and the equations used in the calculations can be found in section S1 in SI.

2.3.1. Aircraft

Two modes of air transport were considered: flights with conventional aircraft and flights with electric aircraft. Reference vehicles for conventional aircraft were ATR72 turboprop aircraft on routes up to 400 km and Airbus A320 jet engine aircraft on routes longer than 400 km. These are the most common aircraft types on domestic routes in Finland and across the Baltic Sea to Estonia and Sweden. The CO_2-eq emissions per passenger kilometer presented in table 2 are based on Baumeister *et al* (2020).

Two fully electric aircraft models are expected to enter commercial use in the coming years: the nine-seater Eviation Alice in 2023 (Eviation 2021) and the 19-seater Heart Aerospace ES-19 in 2026 (Heart Aerospace 2021). Heart Aerospace ES-19 will have a 720 kWh Li-ion battery and an operating range of 400 km, and it was used as the reference vehicle on routes up to 400 km, whereas Eviation Alice will have a 920 kWh NMC battery and an operating range of 815 km. It was used as the reference vehicle on routes longer than 400 km. With the load factor of 0.73, the energy consumption of Heart Aerospace ES-19 is 0.130 kWh pkm^{-1} and the energy consumption of Eviation Alice is 0.172 kWh pkm^{-1}. The lifespan of the electric aircraft batteries was estimated to be 1000 full cycles, which is conservative, but reasonable due to the demanding application.

The travel times of conventional and electric aircraft were based on the travel times of existing flights, but the lower cruising speed of electric aircraft was accounted for. Instead, shorter airport waiting times for electric aircraft were used, as the smaller size of electric aircraft allows for shorter loading and unloading times and the use of smaller airports. See table S2 in SI for more detail on waiting times.

2.3.2. Train

Emissions from traveling by train were calculated using the most common train models in Finland operated by the state-owned Finnish Railways VR as a reference. The majority of the Finnish and Swedish rail networks, as well as the routes selected for this study, have been electrified.

For airport trains in Helsinki and in Stockholm, the reference vehicle was VR's FLIRT Sm5 train, which has an energy consumption of 0.071 kWh pkm^{-1} with a load factor of 0.35 (VTT 2017). To provide faster connections between the major cities in Finland, there are currently two high-speed rail (HSR) corridors planned: Helsinki to Turku (One Hour Train 2021) and Helsinki to Tampere (Finland Railway 2021). For these rail connections, the energy consumption of a high-speed train with a load factor of 0.40 was estimated to be 0.097 kWh pkm^{-1}, which is in line with Baumeister *et al* (2020) and Prussi and Lonza (2018). For other electrified train connections between the cities, the reference vehicle was VR's double-decker InterCity Sr2 train, which has an energy consumption of 0.054 kWh pkm^{-1} with a load factor of 0.40 (VTT 2017).

The only non-electrified rail sections in the selected routes were the Parikkala–Savonlinna rail and the Tallinn–Tartu rail, for which the CO_2-eq emissions were calculated based on the average emissions

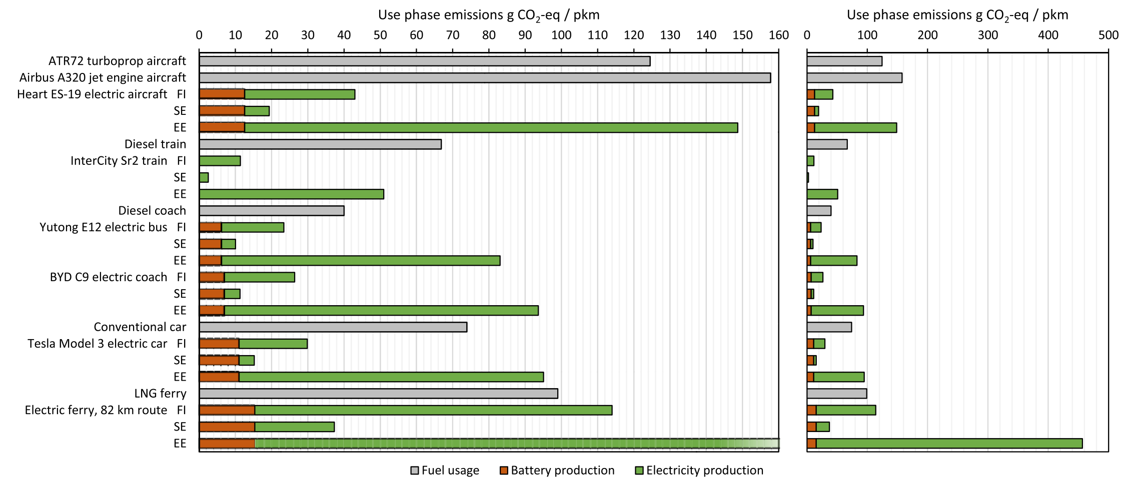

Figure 2. Comparison between use phase emissions of electric transport modes in Finland (FI), Sweden (SE) and Estonia (EE). The emissions of conventional transport modes represent those typical in Finland. The right figure is for illustrating the large use phase emissions of electric ferry when Estonian electricity is used for charging.

of a diesel train in Finland, which are 66.85 g CO_2-eq pkm^{-1} with a load factor of 0.40 (VTT 2017). The travel times were based on the timetables of existing connections. The estimated time savings of the HSR were considered in the rail sections between Helsinki–Turku and Helsinki–Tampere.

2.3.3. Bus

The CO_2-eq emissions for short connecting trips, such as those from the airport or harbor to the railway stations, were calculated according to the emissions of an electric bus because public bus traffic in Helsinki and in other major Finnish cities is predicted to become electrified in the coming years (IEA 2020). The Yutong E12 electric bus, which has 39 passenger seats, a 375 kWh LFP battery and an operating range of 300 km, was used as a reference for the calculations. In accordance with Nordelöf *et al* (2019), the battery was estimated to last 6 years with 65 000 km annual driving before replacement, which equals a lifespan of 390 000 km, or 1300 full cycles.

On routes between the studied cities, two bus options were considered: diesel coach and electric coach. The CO_2-eq emissions of the average diesel coach in highway driving in Finland is 40 g CO_2-eq pkm^{-1} with a load factor of 0.28 (VTT 2017). The reference vehicle for electric coach was BYD C9, which has 49 passenger seats, a 352 kWh LFP battery, and an operating range limited to 300 km. Similar to the electric bus battery, the electric coach battery was estimated to have a lifespan of 390 000 km. The routes and travel times for diesel coach and electric coach were estimated based on existing regional bus connections.

2.3.4. Car

The CO_2-eq emissions for conventional car were calculated from average emissions of gasoline and diesel cars in Finland, which were 151.1 g CO_2-eq km^{-1} for gasoline cars and 125.1 g CO_2-eq km^{-1} for diesel cars in 2019 (VTT 2020). The share of driven mileage for gasoline cars was 59% and for diesel cars 41% (VTT 2017). The average CO_2-eq emissions when traveling by conventional car were 73.92 g CO_2-eq pkm^{-1}, assuming a five-seater car and using a typical load factor of 0.38.

The reference vehicle for electric cars was a Tesla Model 3 Long Range, which has a 75 kWh NCA battery and a usable range of approximately 460 km. According to Tesla (Tesla 2019), the battery is designed to outlast the car. The lifespan of the Model 3 battery was assumed to be 300 000 km (approximately 650 full cycles), which is a typical life cycle for passenger cars in Finland, in line with the estimated battery life of a modern EV (Hoekstra 2019), and below the expected lifespan of Tesla cars (320 000 km) (Tesla 2019).

The distances and travel times for car routes were determined by Google Maps. Although the Model 3 has a usable range of 460 km, charging was included in the travel times for routes longer than 350 km to avoid unnecessary draining of the battery.

2.3.5. Ferry

On routes crossing the Baltic Sea, a ferry ride is necessary for transport modes other than flying. Currently most of the ferries operating on the Baltic Sea are powered by diesel engines, but there is a clear shift towards cleaner ferries powered by liquefied natural gas (LNG). Therefore, the reference vessel used in the calculations was the LNG ferry operating on Helsinki–Tallinn route, which has GHG emissions of 99 g CO_2-eq pkm^{-1} (VTT 2017).

In addition to the conventional ferry, the use of an electric ferry was considered on routes including Helsinki–Tallinn (82 km) or Vaasa–Umeå (96 km) trips. An electric ferry was not considered for the

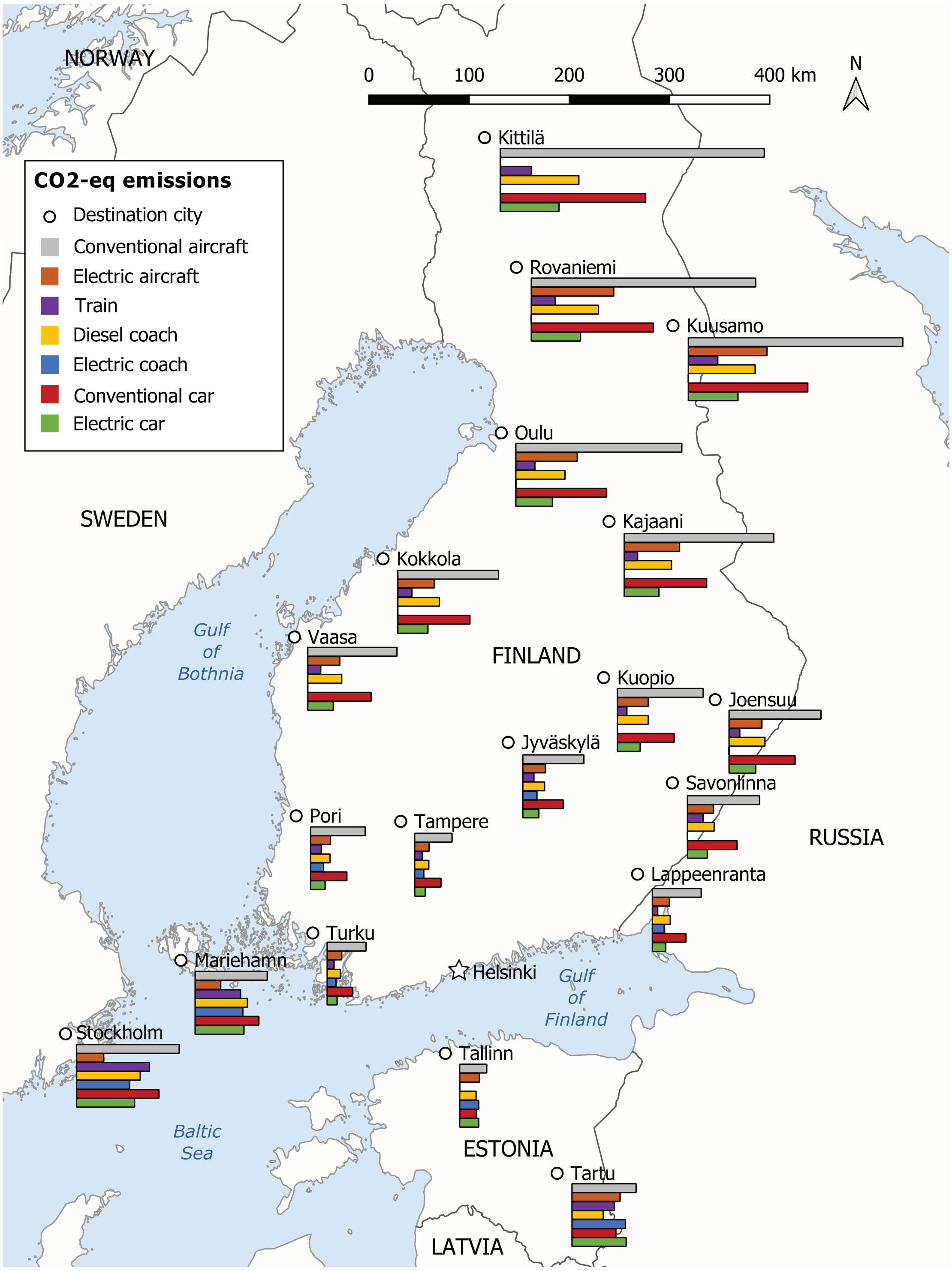

Figure 3. CO_2-eq emissions of different transport modes on routes starting from Helsinki. See figures S1, S3 and S5 in SI for numerical values.

route from Turku to Stockholm due to the length of the route. The electricity consumption and required battery capacity for the electric ferry were calculated based on the data from the e-ferry project Ellen (E-Ferry project 2020). More detailed information about the electric ferry can be found from table S3 in SI.

The travel times for conventional (LNG) ferries were based on timetables for existing connections. The travel times for electric ferries were calculated assuming average travel speed of 13.5 knots, which is the service speed of the e-ferry Ellen (E-Ferry Project 2020).

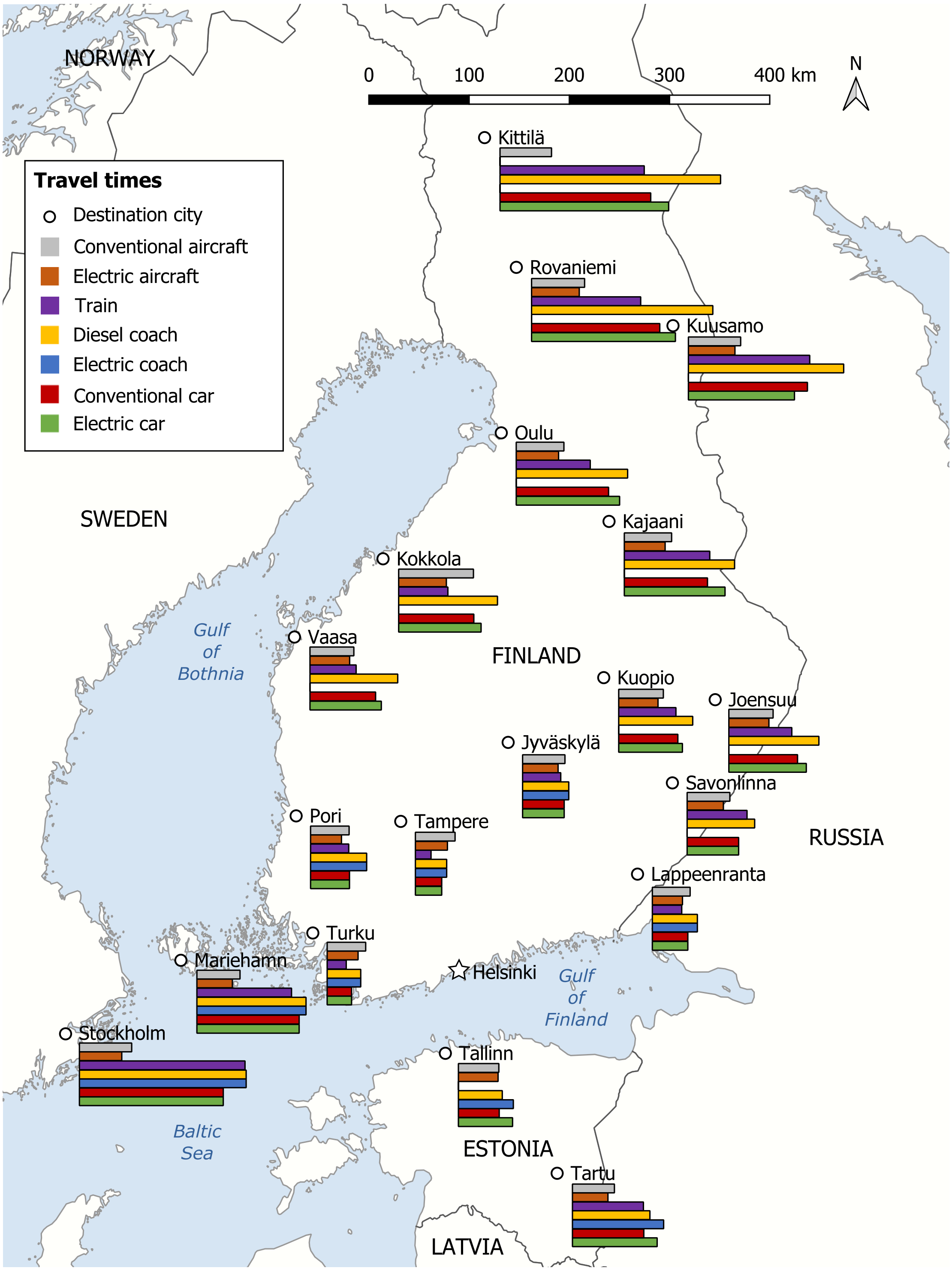

Figure 4. Travel times of different transport modes on routes starting from Helsinki. See figures S2, S4 and S6 in SI for numerical values.

3. Results and discussion

3.1. Effects of electricity carbon intensity and battery production emissions

Figure 2 presents the use phase emissions of electric transport modes calculated with the carbon intensities of the Finnish, Swedish and Estonian electricity grids. The results show that the carbon intensity of the electricity grid greatly influences the total use phase emissions of the electric transport modes, which is in line with the results of the sensitivity analysis by Ellingsen *et al* (2016) on the effect of electricity carbon intensity on EV lifecycle emissions. Moreover, figure 2 shows that the share of battery production emissions in total emissions per pkm depends on the carbon intensity of the electricity used for charging. For Estonia, battery production played a minor role in the overall emissions,

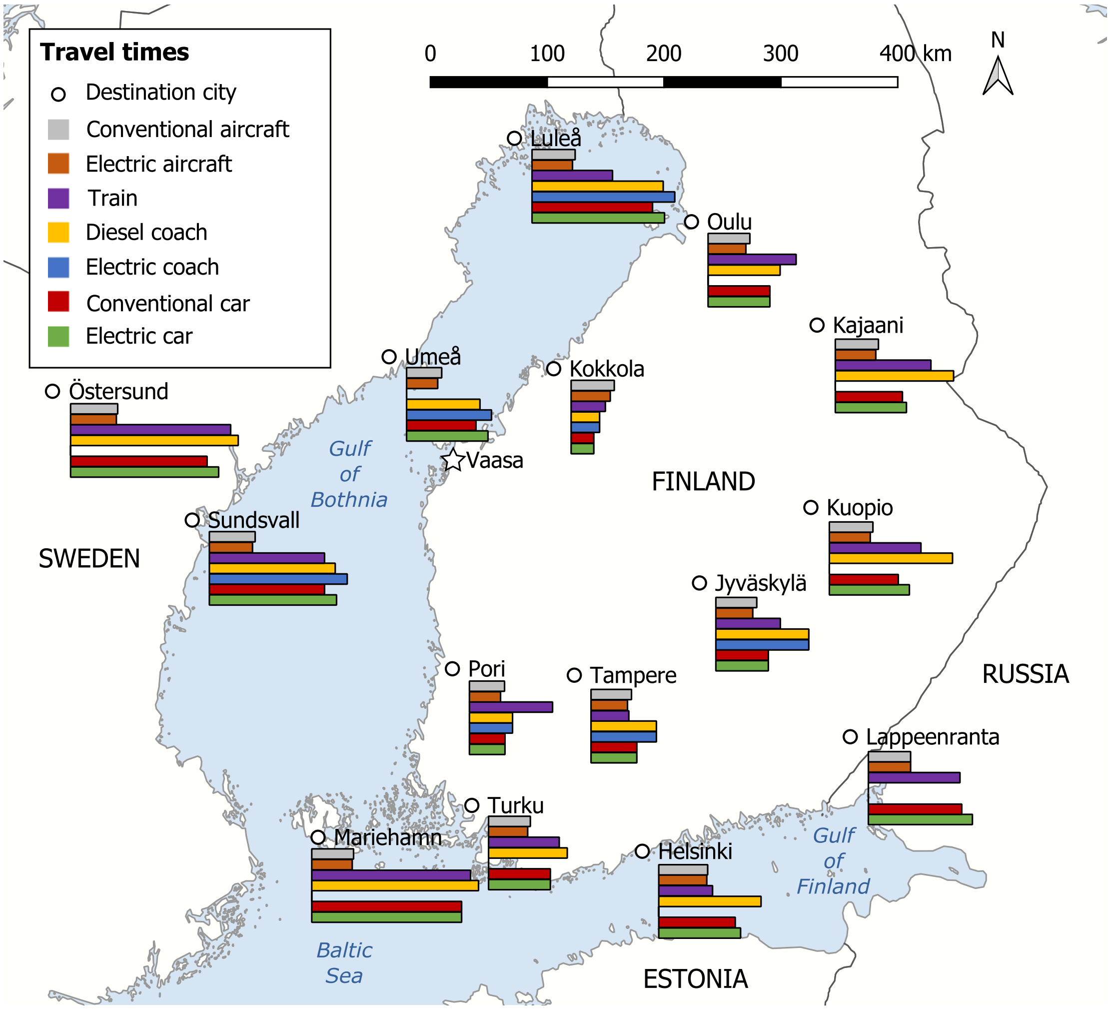

Figure 5. Travel times of different transport modes on routes starting from Vaasa. See figures S8 and S10 in SI for numerical values.

but for Sweden battery production emissions were higher than the emissions from electricity production. Battery production emissions form a significant share of the overall emissions per pkm and should always be considered when comparing the emissions of electric transportation modes with those of conventional ones. In addition, these results are based on the electricity carbon intensity at the beginning of the vehicle's lifecycle. Carbon intensity can be expected to decrease during the vehicle's lifecycle, which would reduce the average use phase emissions per pkm (Hoekstra 2019).

3.2. Domestic routes in Finland

On domestic routes in Finland where trains are mainly running on electric lines, trains show the lowest emissions on all routes (figure 3 and section S3.1 in SI). Even new electrified transportation modes such as electric cars, buses or aircraft cannot outperform the train. Electric buses can nearly achieve low emissions similar to those of electric trains, but their range is limited to 300 km. While conventional aircraft show the highest emissions, electric aircraft applied on the same routes could cut emissions significantly, reaching emissions levels of conventional buses while clearly outperforming conventional cars.

In terms of door-to-door travel times on domestic routes from Helsinki, the train on the high-speed lines to Tampere and Turku is by far the fastest option, followed by car (figure 4). Coaches and electric aircraft perform about the same, and conventional aircraft is the slowest option. By increasing distance up to 400 km, car and coach travel become the slowest options while the higher travel speed of electric and conventional aircraft stands out. Trains can compete with the travel times of the aircraft on routes utilizing the Helsinki–Tampere HSR link, but on routes not benefitting from the HSR the train is slower than the aircraft. However, on routes beyond 400 km the aircraft is by far the fastest option. These findings are in line with earlier studies conducted by Baumeister (2019) and Ryley and Leung (2020).

In terms of door-to-door travel times on domestic routes from Vaasa, car and coach travel is the fastest option to the nearest destination Kokkola (figure 5 and section S3.2 in SI). On routes to Pori, Tampere

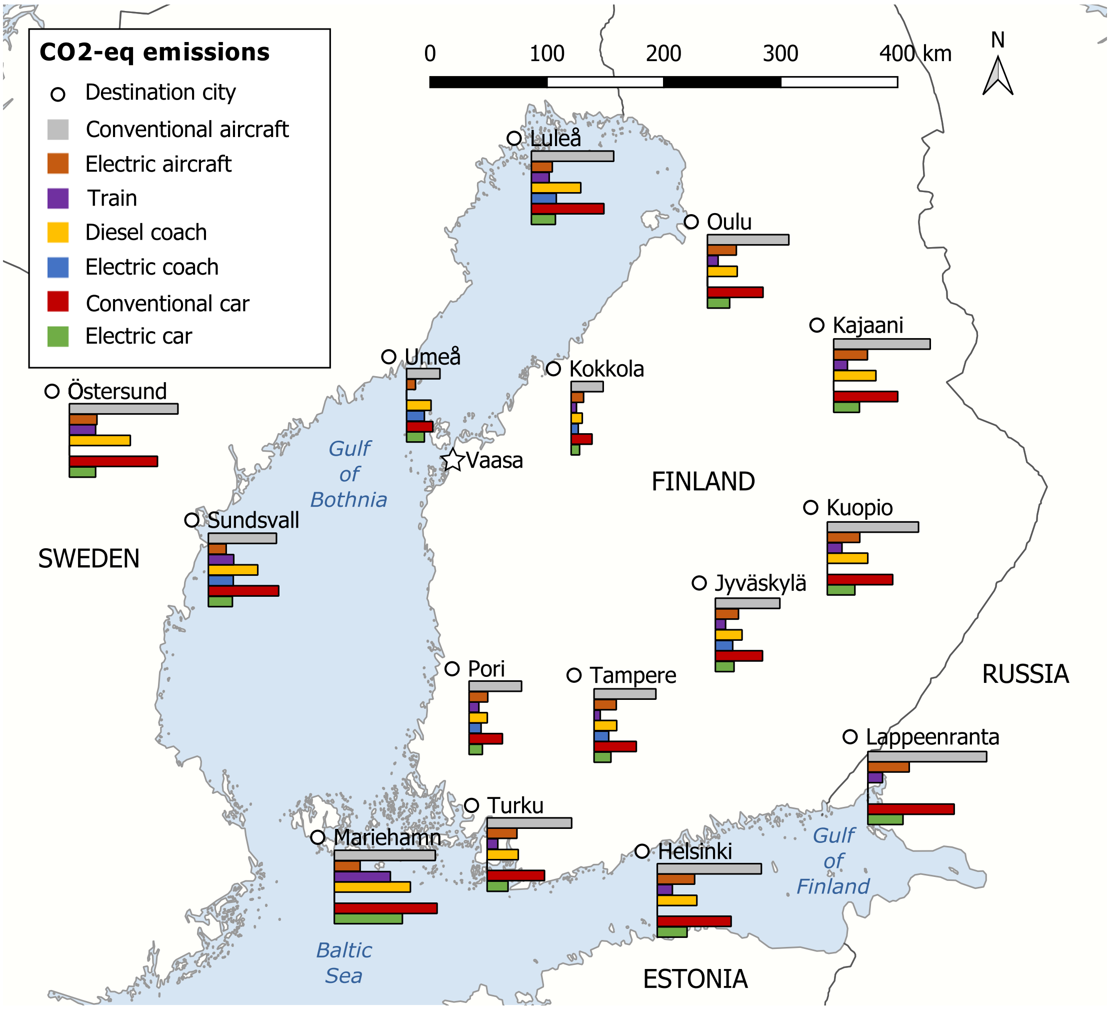

Figure 6. CO_2-eq emissions of different transport modes on routes starting from Vaasa. See figures S7 and S9 in SI for numerical values.

and Jyväskylä car and coach can still keep up with the aircraft, while on longer routes the electric and conventional aircraft are clearly faster. The train can only keep up with other modes on the routes to Tampere and Helsinki due to the structure of the Finnish railway network, which provides good connections between Helsinki and all major Finnish cities but not between major cities.

Although new electrified transportation modes such as electric car, bus or aircraft cannot outperform the train in terms of emissions, the electric aircraft can at least, over distances beyond 400 km, provide fast connections with significantly lower emissions than conventional aircraft (figure 6). On routes from Vaasa (other than Tampere and Helsinki) cars and coaches are a faster alternative to the train on shorter routes and electric aircraft on longer routes. Replacing conventional cars with electric cars could more than halve the emissions from car travel while the travel times would remain more or less the same (only beyond 350 km electric cars are slightly slower due to battery charging). The same applies to the shift from diesel buses to electric buses. Here, however, it needs to be noted that electric buses are limited to a range of 300 km. The replacement of conventional with electric aircraft would mean a significant cut in emissions while it would also mean a slight reduction in travel times due to smaller aircraft size and leaner operations. Finally, replacing conventional car travel with electric aircraft would make sense, as the emissions of electric aircraft are smaller. In terms of diesel coaches a replacement with electric aircraft would as well be feasible as both modes reach similar emissions levels while the electric aircraft offers shorter travel times.

On domestic routes between Helsinki and major Finnish cities up to 400 km, a modal shift to the train is recommended. On routes beyond 400 km, electric aircraft is the most feasible option. On domestic routes between major Finnish cities, where no direct rail link exists, the use of electric aircraft is recommended on routes beyond 300 km because the emissions are below those of conventional car and on comparable levels to diesel coach.

3.3. Routes across the Baltic Sea

On routes across the Baltic Sea to Sweden and the Åland Islands conventional aircraft and cars show the highest amount of emissions whereas electric aircraft the lowest (figures 3 and 6). But also all other modes, due to the use of ferries (conventional or electric) end up producing higher emissions than electric aircraft. The only exceptions here are the routes from Vaasa to Luleå and Östersund. Luleå can be reached faster on land from Vaasa (train to Kemi and then bus to Luleå) while in the case of Östersund, despite the need for a ferry ride, a large part of the journey is completed by train in Sweden, benefiting from the low emissions in electricity production in Sweden. The same accounts for electric cars and electric coaches on routes in Sweden that show lower emissions than their conventional counterparts. However, on all routes electric aircraft clearly provide the shortest travel times because all other modes rely on crossing the Baltic Sea, which is time consuming.

On routes across the Baltic Sea to Estonia, conventional transportation modes outperform electric modes, which is due to the energy mix in Estonia's electricity production. Crossing the Baltic Sea by electric ferry while traveling by electric car and electric coach produces twice the amount of emissions than making the same trip by conventional car or coach sailing on an LNG ferry. Conventional cars and coaches crossing the Baltic Sea by LNG ferry perform at a similar level as diesel trains as well as the electric aircraft. The real surprising finding, however, was that even the emissions of conventional aircraft are lower than those of electric cars and coaches. Regarding travel times, the aircraft has only a slight advantage over the other modes crossing the Baltic Sea. However, on the route to Tartu electric aircraft is clearly faster.

Crossing the Baltic Sea by ferry is rather time consuming and almost as carbon intensive as by conventional aircraft while in the case of the electric ferry to Estonia even more carbon intensive. Electric aircraft on the other side could combine the advantage of a fast crossing by air with much lower emissions. Nevertheless, these results underlined the significant role of carbon intensity in electricity production on the performance of electric transportation modes, complementing earlier findings by Zhang and Fujimori (2020) and Moro and Lonza (2018).

On routes across the Baltic Sea to the Åland Islands and Sweden, the best option in terms of emissions and travel time is the electric aircraft. On routes to Estonia, the use of electric aircraft is also be recommended, although compared to conventional aircraft the emissions reductions are not as high as on domestic Finnish or routes to Åland Island and Sweden due to the energy mix in Estonia. Using electric modes to Estonia is not recommended because they produce higher emissions than conventional modes do, exceeding even those of conventional aircraft.

4. Conclusions

The aim of this study was to provide a holistic view on the carbon dioxide emission reduction potentials of a modal shift from existing to fully electric transportation modes, considering not only land-based but also water-based and airborne transportation modes. Our study found that electric transportation modes possess great potential for emissions reduction. Nevertheless, depending on the energy mix used for electricity production, in some cases emissions of electric transportation modes might exceed those of existing modes. In such cases, a modal shift is not recommended. The emissions generated by battery production can also have a significant share of the total emissions of electric transportation modes and should always be considered.

While also taking into account the door-to-door travel times, our study identified the great potential of electric aircraft in providing a less carbon intensive transportation option paired with short travel times. Especially on routes beyond 300 km and where no HSR exists, electric aircraft represent a viable alternative to electric trains as well as to conventional aircraft, cars and buses. However, on shorter routes across water, electric aircraft could also provide significant benefits compared to conventional aircraft as well as to slower and more carbon-intensive conventional and electric ferries. Finally, our study also found that electric buses are an alternative to electric trains, especially on routes with fewer passengers where trains are less economical to operate.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

ORCID iDs

Samppa Jenu https://orcid.org/0000-0001-7630-9950
Stefan Baumeister https://orcid.org/0000-0002-7197-2662
Jenni Pippuri-Mäkeläinen https://orcid.org/0000-0002-9698-1549
Aino Manninen https://orcid.org/0000-0002-6671-6162
Marko Paakkinen https://orcid.org/0000-0003-4895-8261

References

Baumeister S 2019 Replacing short-haul flights with land-based transportation modes to reduce greenhouse gas emissions: the case of Finland *J. Clean. Prod.* **225** 262–9

Baumeister S and Leung A 2021 The emissions reduction potential of substituting short-haul flights with non-high-speed rail (NHSR): the case of Finland *Case Stud. Transp. Policy* **9** 40–50

Baumeister S, Leung A and Ryley T 2020 The emission reduction potentials of first generation electric aircraft (FGEA) in Finland *J. Transp. Geogr.* **85** 102730

Borken-Kleefeld J, Fuglestvedt J and Berntsen T 2013 Mode, load, and specific climate impact from passenger trips *Environ. Sci. Technol.* **47** 7608–14

Brdnik A P, Kamnik R, Marksel M and Božĭcnik S 2019 Market and technological perspectives for the new generation of regional passenger aircraft *Energies* **12** 1–14

Dai Q, Kelly J C, Gaines L and Wang M 2019 Life cycle analysis of lithium-ion batteries for automotive applications *Batteries* **5** 48

Dalkic G, Balaban O, Tuydes-Yaman H and Celikkol-Kocak T 2017 An assessment of the CO_2 emissions reduction in high speed rail lines: two case studies from Turkey *J. Clean. Prod.* **165** 746–61

E-Ferry Project 2020 The E-ferry Ellen information package: evaluation of the performance, economy, environmental impact and passenger reception of the 100% electric ferry (available at: www.conf.eferry.eu/InfoPackage/eFerry_Information_Package.pdf (accessed 7 December 2020))

Ellingsen L A W, Singh B and Strømman A 2016 The size and range effect: life-cycle greenhouse gas emissions of electric vehicles *Environ. Res. Lett.* **11** 054010

Emilsson E and Dahllöf L 2019 Lithium-ion vehicle battery production (IVL Swedish Environmental Research Institute) (available at: www.ivl.se/download/18.14d7b12e16e3c5c36271070/1574923989017/C444.pdf (accessed 25 August 2020))

European Comission 2020 Determining the environmental impacts of conventional and alternatively fuelled vehicles through LCA—interim report (available at: https://op.europa.eu/en/publication-detail/-/publication/1f494180-bc0e-11ea-811c-01aa75ed71a1 (accessed 11 September 2020))

Eviation 2021 Eviation alice (available at: www.eviation.co/aircraft/ (accessed 15 June 2021))

Finland Railway 2021 Finland railway (Suomirata) (available at: https://suomirata.fi/ (accessed 3 March 2021))

Finnish Transport Agency 2017 Public transport performance statistics 2015 (available at: https://julkaisut.vayla.fi/pdf8/lti_2017-07_public_transport_web.pdf (accessed 30 August 2021))

Han X, Lu L, Zheng Y, Feng X, Li Z, Li J and Ouyang M 2019 A review on the key issues of the lithium ion battery degradation among the whole life cycle *eTransportation* **1** 100005

Hao H, Mu Z, Jiang S, Liu Z and Zhao F 2017 GHG emissions from the production of lithium-ion batteries for electric vehicles in China *Sustainability* **9** 504

Heart Aerospace 2021 ES-19 (available at: https://heartaerospace.com/ (accessed 15 June 2021))

Hoekstra A 2019 The underestimated potential of battery electric vehicles to reduce emissions *Joule* **3** 1412–4

IEA 2017 CO_2 emissions from fuel combustion, highlights 2017 (available at: www.iea.org/publications/freepublications/publication/CO2EmissionsfromFuelCombustionHighlights2017.pdf (accessed 26 September 2020))

IEA 2020 Global EV outlook 2020 (available at: www.iea.org/reports/global-ev-outlook-2020 (accessed 10 September 2020))

Jung J and Koo Y 2018 Analyzing the effects of car sharing services on the reduction of greenhouse gas (GHG) emissions *Sustainability* **10** 1–17

Kaack L H, Vaishnav P, Morgan M G, Azevedo I L and Rai S 2018 Decarbonizing intraregional freight systems with a focus on modal shift *Environ. Res. Lett.* **13** 083001

Kawamoto R, Mochizuki H, Moriguchi Y, Nakano T, Motohashi M, Sakai Y and Inaba A 2019 Estimation of CO_2 emissions of internal combustion engine vehicle and battery electric vehicle using LCA *Sustainability* **11** 2690

Kelly J C, Dai Q and Wang M 2019 Globally regional life cycle analysis of automotive lithium-ion nickel manganese cobalt batteries *Mitig. Adapt. Strateg. Glob. Change* **25** 371–96

Mohr M, Peters J F, Baumann M and Weil M 2020 Toward a cell-chemistry specific life cycle assessment of lithium-ion battery recycling processes *J. Ind. Ecol.* 1–13

Moro A and Lonza L 2018 Electricity carbon intensity in European Member States: impacts on GHG emissions of electric vehicles *Transp. Res.* D **64** 5–14

Nordelöf A, Romare M and Tivander J 2019 Life cycle assessment of city buses powered by electricity, hydrogenated vegetable oil or diesel *Transp. Res.* D **75** 211–22

One Hour Train 2021 One hour train Helsinki–Turku (Tunnin juna) (available at: www.tunninjuna.fi/ (accessed 3 March 2021))

Ortar N and Ryghaug M 2019 Should all cars be electric by 2025? The electric car debate in Europe *Sustainability* **11** 1–16

Peters J F, Baumann M, Zimmermann B, Braun J and Weil M 2017 The environmental impact of Li-ion batteries and the role of key parameters—a review *Renew. Sustain. Energy Rev.* **67** 491–506

Polestar 2020 Life cycle assessment—carbon footprint of Polestar 2 (available at: www.polestar.com/dato-assets/11286/1600176185-20200915polestarlcafinala.pdf (accessed 3 March 2021))

Prussi M and Lonza L 2018 Passenger aviation and high speed rail: a comparison of emissions profiles on selected european routes *J. Adv. Transp.* **2018** 1–10

Rogelj J *et al* 2018 Mitigation pathways compatible with 1.5 °C in the context of sustainable development *Global Warming of 1.5 °C* (Intergovernmental Panel on Climate Change (IPCC)) pp 93–174 (available at: https://www.ipcc.ch/sr15/ (accessed 15 June 2021))

Sivak M and Schoettle B 2016 Transportation emissions in the context of emissions from other economic sectors: 1990–2014 (available at: www.umich.edu/~umtriswt/PDF/SWT-2016-9.pdf (accessed 22 March 2021))

Sun X, Luo X, Zhang Z, Meng F and Yang J 2020 Life cycle assessment of lithium nickel cobalt manganese oxide (NCM) batteries for electric passenger vehicles *J. Clean. Prod.* **273** 123006

Temporelli A, Carvalho M L and Girardi P 2020 Life cycle assessment of electric vehicle batteries: an overview of recent literature *Energies* **13** 2864

Teoh L E, Khoo H L, Goh S Y and Chong L M 2018 Scenario-based electric bus operation: a case study of Putrajaya, Malaysia *Int. J. Transp. Sci. Technol.* **7** 10–25

Tesla 2019 Tesla impact report 2019 (available at: www.tesla.com/ns_videos/2019-tesla-impact-report.pdf (accessed 3 March 2021))

VTT 2017 VTT LIPASTO unit emission database (available at: http://lipasto.vtt.fi/ (accessed 3 March 2021))

VTT 2020 VTT unit emission data 2020

Wu Z, Wang M, Zheng J, Sun X, Zhao M and Wang X 2018 Life cycle greenhouse gas emission reduction potential of battery electric vehicle *J. Clean. Prod.* **190** 462–70

Yang L, Yu B, Yang B, Chen H and Malima G 2021 Life cycle environmental assessment of electric and internal combustion engine vehicles in China *J. Clean. Prod.* **285** 124899

Yuksel T, Tamayao M A M, Hendrickson C, Azevedo I M L and Michalek J J 2016 Effect of regional grid mix, driving patterns and climate on the comparative carbon footprint of gasoline and plug-in electric vehicles in the United States *Environ. Res. Lett.* **11** 044007

Zhang R and Fujimori S 2020 The role of transport electrification in global climate change mitigation scenarios *Environ. Res. Lett.* **15** 034019